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Field-test of a solar low delta-T Stirling engine

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Abstract

The ultimate aim of a Moroccan–German study is to develop a simple solar pumping system, using the concept of low delta-T Stirling engines. This paper describes the main parts of the engine and presents several experimental measurements made under laboratory and field-test conditions in Morocco. Measurements with flat plate cooler and discontinuous motion of the displacer were conducted to verify two essential recommendations of Kolin in expectation of power-output improvements of the gamma-type engine.
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Keywords: Low delta-T Stirling motor; Solar energy; Indicator diagram

1. Introduction

Supplying people with energy is probably one of the most pressing problems facing humanity today. Especially developing countries have an urgent need for simple and cheap energy supply. Many countries are geographically located in areas with intensive solar irradiation. Most of them can be found along the equator or upon vast expansion of desert. Adequate technological solutions are required for using this great potential of energy.

Photovoltaic systems are an elegant and technically mature solution. But in most cases, those countries presently still lack in the expensive high-tech capabilities for the production of PV cells and otherwise imports are limited by the extreme poverty. Therefore other technical solutions are required which fit better in existing domestic production.

A solar thermal engine, based on the Stirling cycle principle is another solution to exploit solar energy, because this engine has the advantage to use an external heat source. Studies about high temperature Dish Stirling engines have been reported in the literature (Shaltens et al., 1992; Bean, 1992). These systems with concentrators and tracking system call upon an advanced and heavy technology.

On the other hand, the low temperature differential (LTD) Stirling engine is a simple method for converting solar heat into mechanical energy. The LTD Stirling engine can operate with small temperature difference between hot and cold side. Several studies and prototypes of LDT Stirling engines have been done. Some of them are as follows:

In 1983, Kolin (1991) introduced the first LTD Stirling engine. This model worked with temperature difference between the hot and cold ends of the displacer cylinder as low as 15 °C.

In 1991, Senft (1991) made a small prototype for demonstration which works already with a temperature difference between hot and cold side lower than 1 °C. In 1993, he described (Senft, 1993) another prototype powered by 60° conical reflector, producing 93 °C in hot side.

In 2005, Kongtragool and Wongwises (2005, 2006) presented the optimum absorber temperature of a once-reflecting full conical concentrator for a low temperature

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Nomenclature

m	masse of gas (kg)	T_H	temperature in hot side (K)
n	speed (rpm)	T_k	temperature in cold side (K)
P	power (W)	v	volume (m^3)
p	pressure (Pa)	v_{max}	maximum volume (m^3)
R	ideal gas constant ($J\,K^{-1}\,kg^{-1}$)	v_{min}	minimum volume (m^3)
S	specific entropy ($J\,kg^{-1}\,K^{-1}$)	W	work (J)
T	temperature (K)	ε	compression ration
T_A	absorber temperature (K)		

differential Stirling engine and provided theoretical investigation of the power output of the gamma-configuration LTD Stirling engine.

In 2006, Kongtragool and Wongwises (2007) designed and constructed two single-acting, twin power piston and four power pistons, gamma-configuration, LTD Stirling engine. Non-pressurized air was used as working fluid. The heater temperature was about 589–771 K.

In 2007, Martaj et al. (2007) presented a thermodynamic analysis of a low temperature Stirling engine at steady state operation. In this theoretical investigation, energy, entropy and exergy balances were presented at each main element of the engine.

In this article, several experimental works on a simple solar LTD Stirling engine, gamma type, are presented. Coupled with a water pump, this engine is intended to supply rural areas in developing countries with water.

Most of he LTD Stirling engines described in the literature were presented as demonstration units or deigned with complicated parts, like concentrator and twin power pistons. In this article, a simple LTD Stirling engine coupled with water pump is described, and several experimental measurements under real conditions are presented. The goal is to develop a simple, robust and useful engine for developing countries. Another contribution of the present work to the field of LTD Stirling engines is the experimental study with discontinuous motion and flat plat heat exchanger.

2. General description of the prototype

At Dresden University of Technology a low temperature differential Stirling engine (gamma type) has been developed. This paragraph summarizes the components of this prototype named SUNWATER@ (two versions: SSM III and SSM IV) coupled with a water pump. The main components of SSM III engine are shown in Fig. 1. Some characteristic data are listed in Table 1.

Principally the well-known Stirling engine transforms external heat of any heat generating process (here: absorbed solar radiation) into mechanical power. The ideal Stirling cycle comprises of two isothermal processes and two isochoric processes (Fig. 2). Fig. 3 schematically shows the operation of SSM III at various stages of the Stirling cycle. As material of the radiation absorber plate, aluminum was chosen with a thickness of 1 mm. The absorber is oriented under an angle of 30°. As working gas the everywhere available and cost-free air is chosen which circulate between the hot side (absorber) and the water-cooled cold side (tubular heat exchanger). The cooling water is taken from the pumped water. The displacer piston, made from plastic foam, moves the air back and forth from hot side to the cold (two isochoric processes). The displacer piston and working piston are connected to a simple crankshaft made of steel. The regenerator is made of metal wire mesh. It must absorb as much heat as possible when the hot air passes from hot to cold side, and on the way back, it must yield up as much heat as possible to the air.

Generally there is a large difference between the ideal Stirling cycle and real cycle: In certain cases the real cycle is five times smaller than the ideal cycle (Werdlich, 1994). To optimize the power – output of a low delta-T Stirling engine, Kolin (1974/1991) gave two recommendations:

- Flat plat heat exchangers instead of tubular heat exchangers.
- Discontinuous motion of displacer instead of commonly used sinusoidal motion.

We applied the first recommendation by producing a flat plat cooler. The new version of the machine is named SSM IV. In order to simplify the construction of this version, we made a horizontal absorber with concavity larger then that of SSM III, so that, it can receive the solar radiation

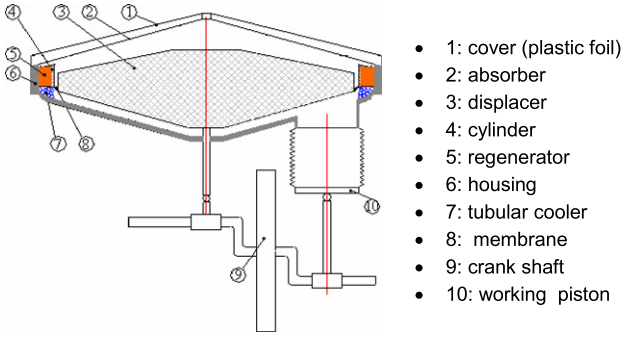

Fig. 1. Components of SSM III.

Table 1
Characteristics of SSM III.

Diameter of absorber	1.6 m	Middle work pressure	1 bar	Absorber-temperature	65–120 °C
Absorber area	1.80 m^2	Power (mech.)	30–40 W	Cooler temperature	20 °C
Height	1.45 m	Height displacer	80 mm	Temperature difference between hot and cold side	>45 °C
Weight	240 kg	Height working piston	190 mm	Speed	30–40 rpm
Work gas	Air	Compression ratio	1.055	Type	Gamma

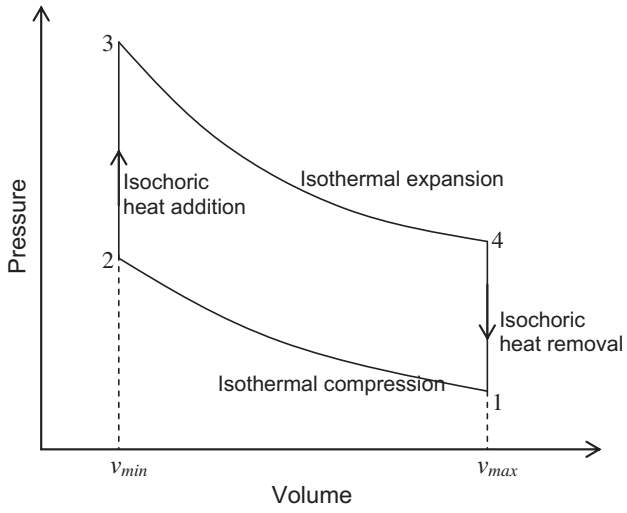

Fig. 2. Ideal Stirling cycle.

without tracking system during the morning and the afternoon (Fig. 4). Fig. 5 shows version SSM IV with the new construction of the cooler. One of the aims of this work is to compare both versions.

3. Experimental study

3.1. Measurements in the laboratory

Experimental tests of SUNWATER[@] were performed to evaluate the behavior of the engine and to be able to optimize its operation afterwards. The first tests were carried out at the laboratory of institute of energy at Dresden University in Germany. The measured parameters are: the temperature of gas at several points in the machine, pressure and volume during the cycles. Temperature measurements and different recordings at different points in the engine were performed by Nickel/Chrome thermocouple (0.1 mm diameter) connected with a data acquisition unit (Fig. 6). A pressure sensor is used too, in order to measure the gas pressure. It is connected with the cold side of the engine. The pressure sensor needs a voltage supply of 12–15 V and supplies a current, which is dependent of the measured gas pressure. Its sensitivity is equal to 2.5 kPa/mA. The measurement of volume is done by the determination of the working piston position. A rheostat delivers a voltage signal according to the position of working piston. In order to draw Clapeyron diagram, pressure and volume of the gas must be measured at the same time.

The measurements in the laboratory were made with a sun simulator made up of several lamps. The average solar radiation of the simulator is 800 W/m^2.

3.2. Measurements under real conditions in Morocco

Experimental measurements on the machine under real conditions are of great importance in its process of design for the following reasons:

– The machine is designed to work under difficult conditions in zones where problems of energy exists (mountain, desert, etc.)

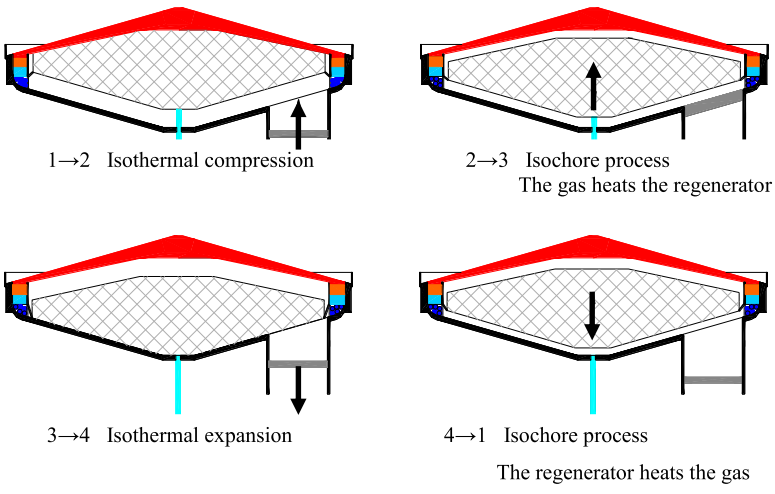

Fig. 3. Working principal of SSM III.

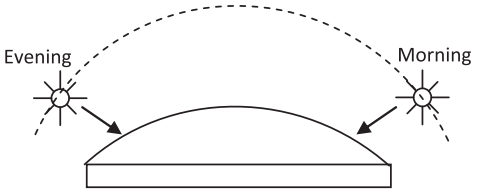

Fig. 4. Horizontal absorber of SSM IV.

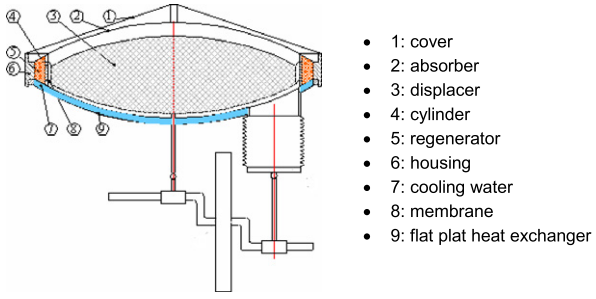

Fig. 5. Components of SSM IV.

– There exists a great difference between the conditions of the laboratory and the real conditions (temperature, humidity, wind, etc.)
– The tests under the real conditions make it possible to understand practical engineering problems of the machine which are unperceived at the laboratory.

For those reasons, experimental measurements were carried out under real conditions in Meknès/Morocco (Fig. 7). Meknès is situated at 140 km east of the Atlantic, north of the high Atlas. Its geographic coordinates are 6° west and 34° north. The measurements were conducted during the period of May to August. Each experiment started at 8:30 a.m. and continued until 4:30 p.m. The solar radiation is measured by a pyranometer.

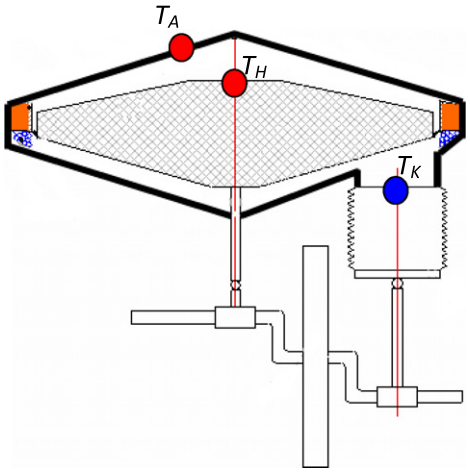

Fig. 6. Positions of thermocouples in SSM III.

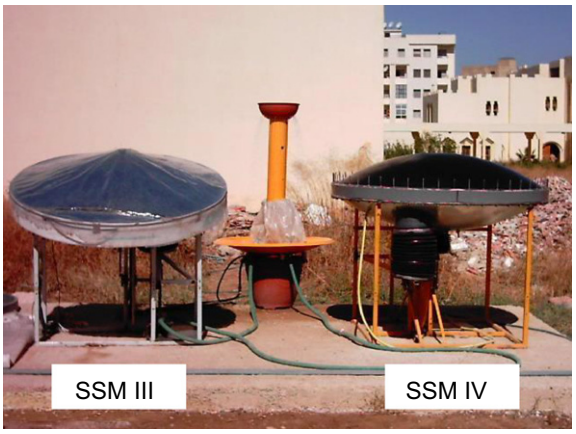

Fig. 7. SSM III and SSM IV under real conditions in Meknes (Morocco).

4. Results and discussion

4.1. Measurement of temperatures

Fig. 8 shows the temperatures of absorber, hot and cold gas side during one cycle under laboratory conditions.

It can be noted that there is an important difference between the temperature of the absorber and that of hot gas. This difference can reach 20 °C. This is due to the fact that the heat transfer coefficient is small because of the low due to the slow displacer movement (low Reynolds number).

With the given "artificial sun" the absorber temperature does not exceed 75 °C in the laboratory. Experimental measurements under real conditions show that the temperature of the absorber can reach 100 °C.

Figs. 9 and 10 represent the daily variation of the solar radiation of a typical summer day and the temperatures of the two machines. It can be concluded that both versions work during 7 h per day with a mean speed of 30 rpm.The adequate pump for this speed is a diaphragm pump.

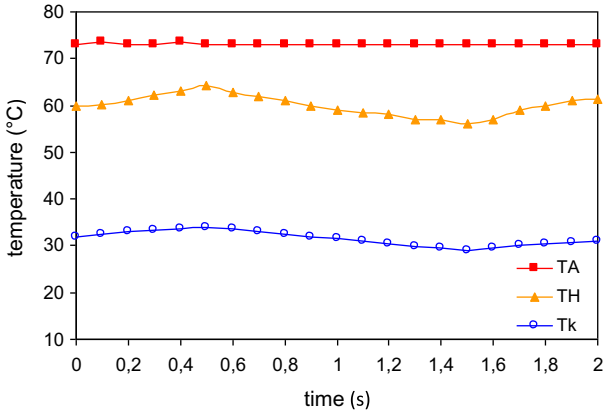

Fig. 8. Measurement of temperatures during one cycle.

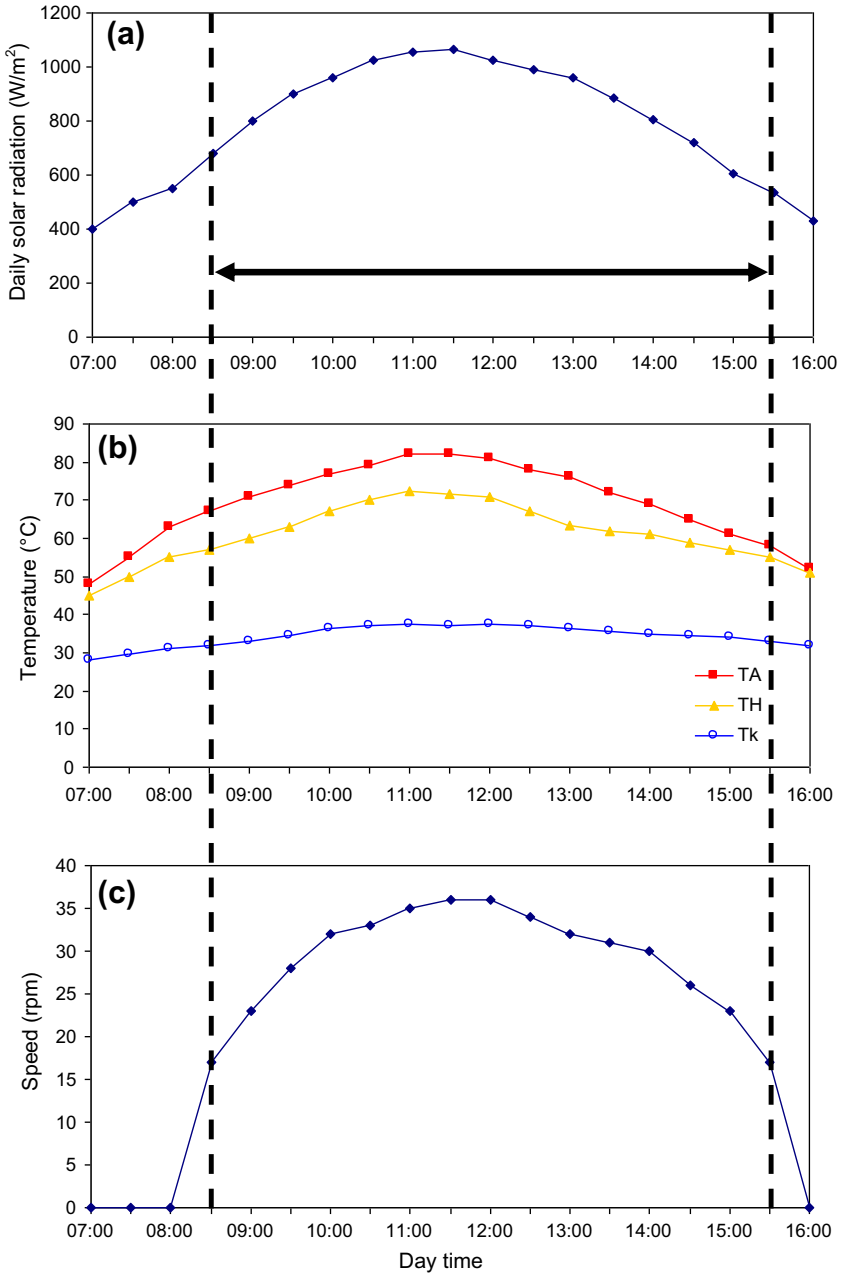

Fig. 9. Measurement of parameters of SSM III. (a) Daily solar radiation, (b) temperature of absorber, hot side and cold side and (c) speed.

When the incoming solar radiation is 900 W/m^2, the absorber area (1.75 m^2) receives 1575 W, and both machines pump about 6 m^3 water per day for 10 m height. Therefore, the hydraulic power of the pumping system is equal to 20.44 W. As a consequence, the efficiency is about 1.3%.

The efficiency of this engine is low compared to that of Photovoltaic systems. Consequently, the total price of its main parts is about 200 Dollars. Therefore, the kilowatt–hour of this engine is high. Nevertheless, the advantage of this prototype is the availability of its mechanical parts in developing countries and the simplicity of its construction. Thus, the engine should be optimized to be manufactured locally.

Kolin (1991) gives a useful formula for the power of "low delta-T" Stirling engine according to the temperature difference between the hot and the cold side. Basis is the well-known expression for the power of a Stirling engine

$$P = m \cdot \Delta T \cdot \Delta s \cdot n \tag{1}$$

with

$$\Delta s = R \ln \frac{v_{\max}}{v_{\min}} = R \ln(\varepsilon) \tag{2}$$

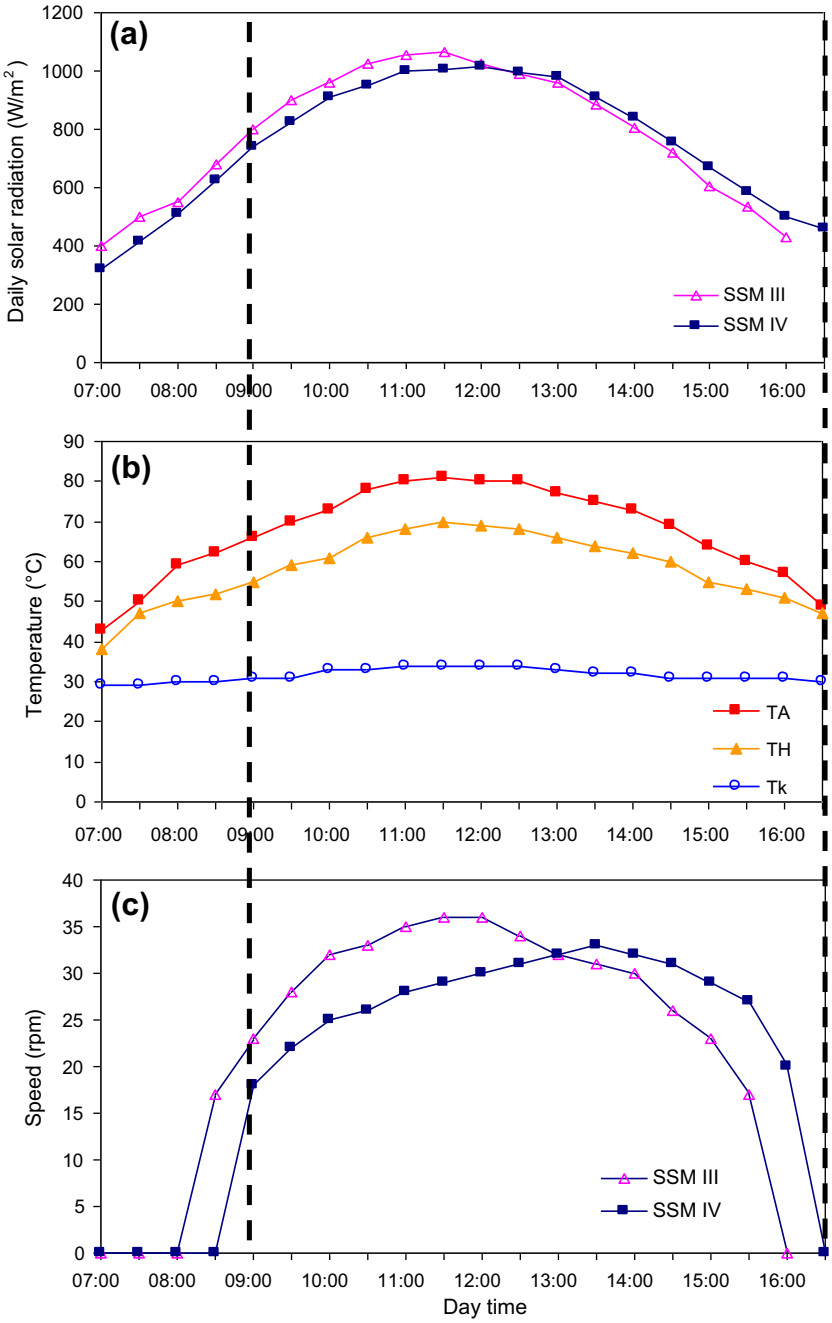

Fig. 10. Measurement of parameters of SSM IV. (a) Daily solar radiation (b) temperature of absorber, hot side and cold side and (c) speed.

Two assumptions were used by Kolin:

$$\varepsilon = 1 + \frac{\Delta T}{1100} \tag{3}$$

and

$$n = k \cdot \Delta T \tag{4}$$

where k is a constant: $k \approx 1$.

Measurements on SUNWATER were made to verify the second assumption. Fig. 11 shows the speed measurement as a function of temperature difference. According to this figure, we deduce that the assumption of Kolin is justified.

The experimental study under field test conditions shows that the absorber temperature varies linearly according to solar radiation (Fig. 12). Measurements show that the transparent cover absorbs and reflects a part of solar radiation (Fig. 13). Nevertheless, the use of this cover is very important for the minimization of the calorific losses by convection, especially under real conditions.

4.2. Measurement of Clapeyron diagram

Fig. 14 shows a comparison of the Clapeyron diagrams of SSM III and SSM IV. The cycle area of SSM IV is lar-

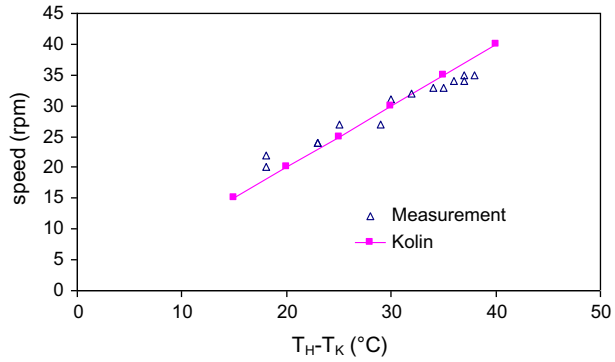

Fig. 11. Speed of SSM III as a function of temperature difference between hot and cold side.

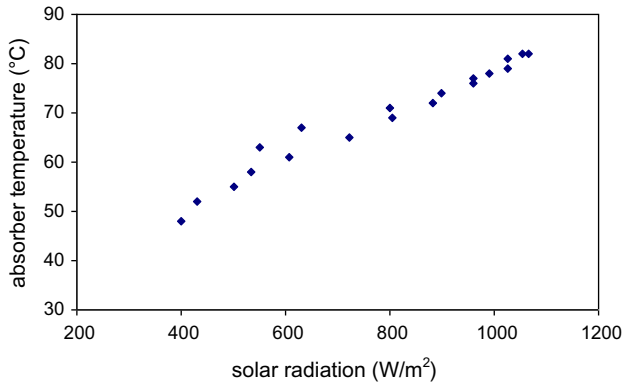

Fig. 12. Variation of absorber temperature with solar radiation.

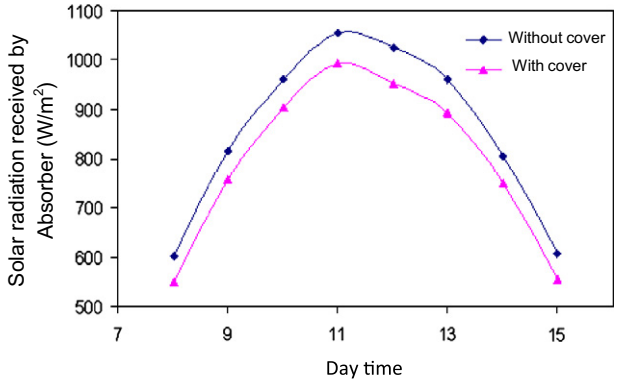

Fig. 13. Solar radiation received by absorber with and without cover.

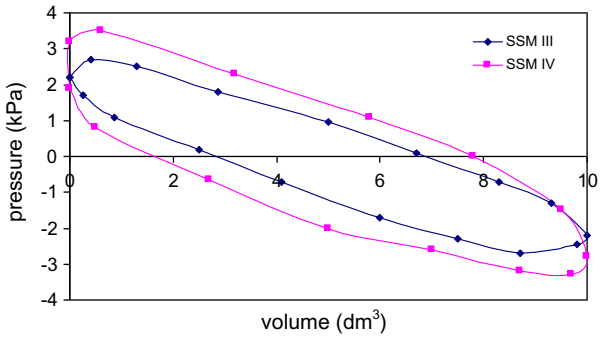

Fig. 14. Clapeyron diagram with different coolers.

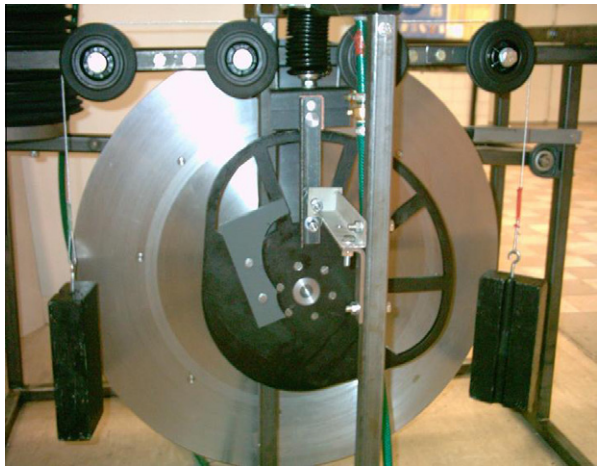

Fig. 15. Cam used to realize the discontinuous motion of displacer.

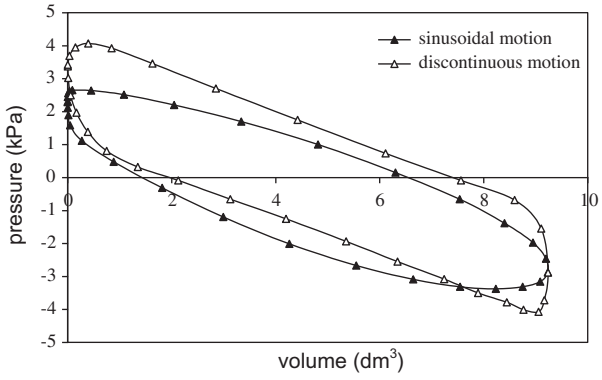

Fig. 16. Clapeyron diagram for continuous and discontinuous motion of displace.

ger. Thus, the flat plat heat exchanger has a positive effect on the engine.

The second recommendation of Kolin – discontinuous motion of the displacer – was also tested. In the Stirling engine with sinusoidal displacer motion, heating and cooling occur simultaneously. Due to this fact the cycle is in two ways less advantageous:

– The compression consumes more work.
– The expansion produces less work.

For SSM IV a discontinuous displacer motion was realized using a mechanism with a cam shown in Fig. 15. Fig. 16 presents the effect of the discontinuous motion on the indicator diagrams. The corners of the cycle are filled, increasing the indicator diagram area, and consequently the engine power, as well.

Even if the cycle work for the discontinuous motion is improved, the machine has complications in its operation, because of the great displacer acceleration required in this

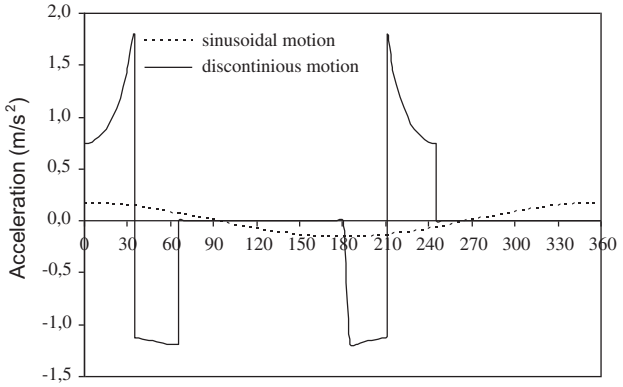

Fig. 17. Acceleration of displacer.

construction and consequently the great forces which the engine must develop. Fig. 17 illustrates the comparison between the accelerations of the displacer with continuous and discontinuous motion.

5. Conclusions

Utilizing the solar energy efficiently and economically in developing countries is the major aim of designing a solar-thermal Stirling engine. In this paper, a low delta-T Stirling engine is described. Experimental data are given for laboratory and field test conditions.

The new construction with the discontinuous motion of the displacer affects mechanical stability of the engine negatively because of high forces required by this configuration. Therefore the sinusoidal motion is preferred. However, an alternative to improve the power output is the use of a flat plate heat exchanger for the cooler.

For further optimization of the engine and its applications, the following points should be studied:

- The heat transfer between the absorber and the gas must be improved, since the power is proportional to the cube of the difference in temperature between the hot part and the cold part.
- The mechanical energy generated by the machine can be transformed into electrical energy instead of the hydraulic power of pumping, together with an accumulator for storage. In this case, air cooling should be envisaged instead of water cooling.

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